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USING SEDIMENT 'FINGERPRINTS' TO ASSESS SEDIMENT-BUDGET ERRORS, NORTH HALAWA VALLEY, OAHU, HAWAII, 1991–92

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ABSTRACT

Reliable estimates of sediment-budget errors are important for interpreting sediment-budget results. Sediment-budget errors are commonly considered equal to sediment-budget imbalances, which may underestimate actual sediment-budget errors if they include compensating positive and negative errors.

We modified the sediment 'fingerprinting' approach to qualitatively evaluate compensating errors in an annual (1991) fine (<63 µm) sediment budget for the North Halawa Valley, a mountainous, forested drainage basin on the island of Oahu, Hawaii, during construction of a major highway. We measured concentrations of aeolian quartz and ^{137}Cs in sediment sources and fluvial sediments, and combined concentrations of these aerosols with the sediment budget to construct aerosol budgets. Aerosol concentrations were independent of the sediment budget, hence aerosol budgets were less likely than sediment budgets to include compensating errors. Differences between sediment-budget and aerosol-budget imbalances therefore provide a measure of compensating errors in the sediment budget.

The sediment-budget imbalance equalled 25 per cent of the fluvial fine-sediment load. Aerosol-budget imbalances were equal to 19 per cent of the fluvial ^{137}Cs load and 34 per cent of the fluvial quartz load. The reasonably close agreement between sediment- and aerosol-budget imbalances indicates that compensating errors in the sediment budget were not large and that the sediment-budget imbalance is a reliable measure of sediment-budget error.

We attribute at least one-third of the 1991 fluvial fine-sediment load to highway construction. Continued monitoring indicated that highway construction produced 90 per cent of the fluvial fine-sediment load during 1992. Erosion of channel margins and attrition of coarse particles provided most of the fine sediment produced by natural processes. Hillslope processes contributed relatively minor amounts of sediment. © 1998 John Wiley & Sons, Ltd.

KEY WORDS: sediment budget; coarse-particle attrition; sediment 'fingerprinting'; tropical geomorphology; highway construction effects; aeolian quartz; ^{137}Cs

INTRODUCTION

Sediment budgets provide a useful framework for quantifying sediment sources and understanding the effects of human activities on sediment transport (e.g. Reid *et al*., 1981; Sutherland and Bryan, 1991). Because erosional processes are spatially variable and difficult to measure, however, sediment budgets inherently contain errors. Accurate assessments of errors greatly enhance the usefulness of sediment-budget studies, particularly when sediment budgets are used to determine effects of land-use practices (Kondolf and Matthews, 1991).

Sediment-budget errors are often considered equal to sediment-budget imbalances, that is, discrepancies between estimates of sediment inputs, outputs and storage changes (Kondolf and Matthews, 1991). Sediment-budget imbalances, however, may underestimate actual sediment-budget errors if they include compensating positive and negative errors (Kondolf and Matthews, 1991).

As an example, a sediment budget might overestimate sediment production by naturally occurring landslides and underestimate sediment production by gullies related to land use by a similar, or compensating, amount. Although the imbalance in the sediment budget would be small, the true importance of the two sediment sources would be seriously misrepresented. Resource management actions based on the sediment budget would quite likely be costly failures in terms of erosion control.

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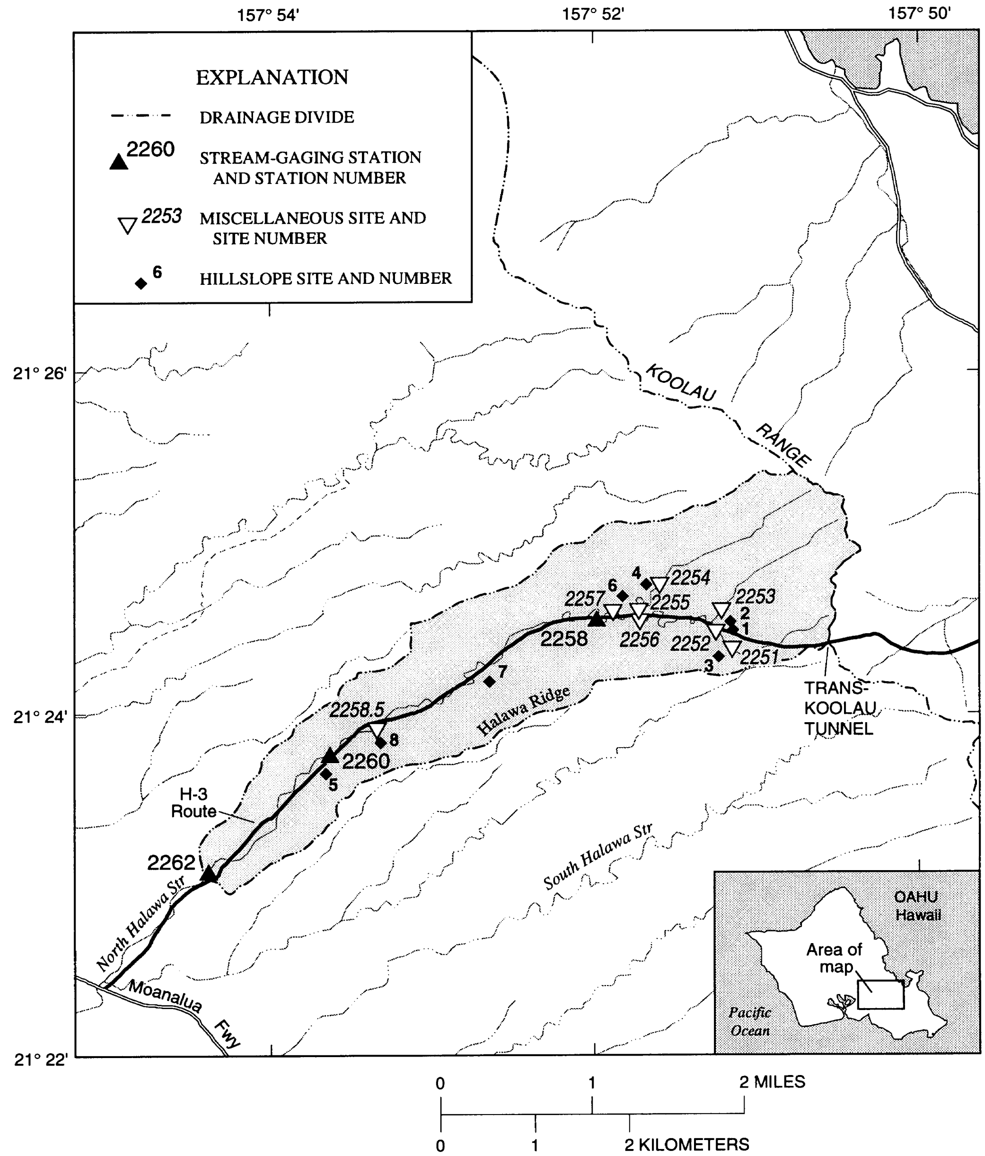

Figure 1. North Halawa Valley study area

Sediment ‘fingerprinting’ (e.g. Peart and Walling, 1986) is an alternative approach to sediment-source quantification. Sediment ‘fingerprints’ consist of sediment characteristics such as chemistry, mineralogy, colour, magnetic properties or radionuclide content that distinguish sources of fluvial sediment (e.g. Peart and Walling, 1988). Concentrations of ‘fingerprints’ in sediment sources can be compared to ‘fingerprint’ concentrations in fluvial sediments to infer the major sources of fluvial sediments (e.g. Sutherland, 1991).

We modified the sediment ‘fingerprinting’ approach to qualitatively evaluate compensating errors in an annual (1991) fine (<63 μm) sediment budget for the North Halawa Valley, a mountainous, forested drainage basin on the island of Oahu, Hawaii (Figure 1). The study objective was to determine the sources of fluvial sediment transported from the valley during construction of a major highway. We measured concentrations of two aerosols, aeolian quartz and ^{137}Cs, in sediment sources and fluvial sediments and combined these measurements with the sediment budget to construct annual aerosol budgets. Aerosol concentrations were

independent of the sediment budget, hence aerosol budgets were less likely than the sediment budget to fortuitously balance as a result of compensating positive and negative errors. Differences between sediment-budget and aerosol-budget imbalances therefore provide a measure of compensating errors in the sediment budget.

Sediment and aerosol budgets were developed using data collected in 1991 (designations of years refer to water years, which begin on 1 October, end on 30 September, and are numbered for the calendar year in which they end). We restricted the study to fine-grained sediment because bedload data were not available and because silt and clay particles are, under most conditions, transported in suspension (Richards, 1982). We continued the sediment-budget monitoring in 1992 , but lacked sufficient data to construct aerosol budgets for 1992.

STUDY AREA CHARACTERISTICS

North Halawa Stream drains the North Halawa Valley on the leeward (southwestern) slope of the Koolau Range (Figure 1). The study area consists of the $10{\cdot}4\,km^2$ drainage basin upstream of US Geological Survey (USGS) stream-gauging station 2262, at an altitude of 49 m (stream-gauging station numbers are abbreviated in this paper; complete numbers are preceded by 16 and end in 00). The overall stream gradient, measured from the headwaters to station 2262, is $0{\cdot}074\,m\,m^{-1}$, and basin relief is 814 m. Mean velocities computed for bankfull conditions ranged from $1{\cdot}10$ to $2{\cdot}29\,m\,s^{-1}$, and bankfull Reynold's numbers ranged from $0{\cdot}21\times10^6$ to $1{\cdot}78\times10^6$. Bed material consists of boulders, cobbles and gravel, with small amounts of finer sediment.

Average annual rainfall in North Halawa Valley ranges from about 1000 to 3800 mm a^{-1} (US Department of Commerce, 1961). Rainfall is related to altitude, and is highest near the crest of the Koolaus as a result of orographic lifting and cooling of marine air masses moving over the Koolau Range with the prevailing northeasterly trade winds (Wentworth, 1942; Mink, 1959). Rainfall varies seasonally, with most precipitation falling between November and April.

The Koolau Range is the eroded remnant of the larger and younger of two major shield volcanoes that formed the island of Oahu (Stearns and Vaksvik, 1935). Lithology of the study area consists of basalt that was extruded in numerous gently dipping, thin (<3 m) flows of aa and pahoehoe lava (Visher and Mink, 1964).

The lower valley, below an altitude of about 300 m, is deeply eroded and roughly U-shaped in cross-section. Unweathered bedrock is exposed in small scarps along valley walls (Izuka, 1992). The active channel is incised 1–2 m into alluvium, and a few small ephemeral tributaries enter from steep adjacent hillslopes that are mantled with colluvial deposits (Izuka, 1992).

The upper valley, at altitudes greater than 300 m, includes several tributary canyons that are V-shaped in cross-section. Chemical weathering of bedrock extends tens of metres below the land surface (Wentworth, 1942; Izuka, 1992). Alluvial deposits are absent along tributary channels (Izuka, 1992). The ridges and crest of the Koolau Range that bound the North Halawa Valley display the classic 'knife-edge' morphology described by Wentworth (1943).

North Halawa Valley was inhabited and used for farming by native Hawaiians (Spear, 1990). Parts of the lower valley were used for agriculture between 1850 and 1947 (Spear, 1990, 1991). A major reforestation project was undertaken in 1910–11 to control erosion (Spear, 1991). The valley is presently uninhabited.

Construction of the H-3 freeway in the North Halawa Valley began in November 1987 and continues at present (1997). Construction activities have increased suspended-sediment loads at station 2262 (Hill and DeCarlo, 1991; Hill, 1996). As of September 1991, highway construction affected about 4 per cent of the drainage basin area upstream of station 2262 and involved about $404\,000\,m^3$ of cut and $72\,900\,m^3$ of fill (Q. D. Truong, Parsons Brinkerhoff Quade & Douglas, Inc., written communication, 1993).

Quartz in soils of the leeward Koolau Range originates solely from aeolian transport of dust from Asia (Jackson *et al*., 1971). Quartz content of soils from ridge crests in the Koolaus ranges from $0{\cdot}8$ to $3{\cdot}4$ per cent (Jackson *et al*., 1971). Quartz particles are mostly in the 2–10 µm size range (Rex *et al*., 1969; Jackson *et al*., 1971) and are distributed to depths of about 7 cm in ridgetop soils of the Koolau Range (Jackson *et al*., 1971).

^{137}Cs, a radioactive product of nuclear fission, has a half-life of $30{\cdot}2$ years and was distributed worldwide with atmospheric fallout following atmospheric testing of nuclear weapons during the 1950s and early 1960s (e.g. Sutherland, 1991). Maximum fallout rates were measured on Oahu in 1963–64 (Health and Safety

Laboratory, 1977). Deposition of ^{137}Cs was negligible during the 1991–92 study period (e.g. Ritchie and McHenry, 1990). ^{137}Cs, an alkali cation, is strongly bound to cation-exchange sites of clays and is largely irreversibly bound in fresh-water systems. ^{137}Cs generally exhibits an exponential decrease with depth in undisturbed soils (Ritchie and McHenry, 1990).

METHODS

We constructed annual fine-grained sediment budgets (henceforth 'sediment budgets') from field and laboratory measurements of sediment transport in North Halawa Valley. Previous investigations in the Koolau Range (Stearns and Vaksvik, 1935; Wentworth, 1928, 1943; White, 1949; Scott and Street, 1976; Peterson *et al*., 1993) indicated that debris flows, soil creep and channel erosion were probably the most important natural erosional processes, and these were the processes that we monitored in the field. We included estimates of fine-grained sediment produced by *in situ* weathering and subsequent erosion and by attrition of coarse particles during fluvial transport. Because of difficulties in directly measuring sediment transport from construction sites (e.g. Riley, 1990), we estimated sediment loads originating from highway construction with a regional regression.

Drainage-basin budgets for quartz and ^{137}Cs were based on the 1991 sediment budget and average concentrations of quartz and ^{137}Cs in sediment sources and fluvial sediments. The quartz budget included an estimate of atmospheric deposition.

Fluvial sediment transport at station 2262

Streamflow and suspended-sediment discharge were monitored at station 2262 (Figure 1) using standard practices of the USGS (Porterfield, 1972; Rantz *et al*., 1982a,b; Edwards and Glysson, 1988). Recurrence intervals of annual peak flows at nearby station 2260 were determined using methods of the US Interagency Advisory Committee on Water Data (1981) with 42 years of data. Suspended-sediment samples were collected with automatic point samplers (442 samples in 1991, 138 in 1992) and with manual depth-integrating cross-section samplers (24 samples in 1991, 20 in 1992). Point samples were collected daily when stream stage was above a threshold level, and at intervals of 45 or 90 min when stage exceeded a higher threshold level. Fewer samples were collected in 1992 than in 1991 as a result of long periods of low and zero streamflow. Cross-section samples were collected for a wide range of flow conditions, and particularly during high flows. Laboratory analyses for suspended-sediment concentration and particle-size distribution were made at the USGS laboratory in Honolulu, using methods described by Guy (1969).

Estimation of highway construction effects

Fine-sediment loads resulting from highway construction were estimated using a regional regression. The regression used measured annual suspended-sediment yields and corresponding annual runoff depths for leeward Koolau basins in natural forest cover, with only small areas affected by residential or agricultural development. Data used for the analysis included pre-construction data for North Halawa Stream (Hill, 1996) and data reported for nearby basins in previous studies (Jones *et al*., 1971; Doty *et al*., 1981; Shade, 1984).

Suspended-sediment yields were first converted to fine-sediment yields by multiplying by the average proportion of fine material in suspended-sediment samples, collected at the stations used in the regression analysis (87·5 per cent, using data from USGS data files). Data were then transformed to common logarithms before computing the regression, which took the form:

$$\log Sy = -3{\cdot}52 + 2{\cdot}02 \times \log R \tag{1}$$

where Sy is annual fine-sediment yield (in Mg km^{-2}) and R is annual runoff depth (in mm). The standard error of the regression was 0·22 in log units, and the coefficient of determination was 86·1 per cent.

Annual fine-sediment yields attributable to natural erosion were estimated with Equation 1 using measured annual runoff depths at station 2262 during 1991 and 1992. These regression estimates were corrected for back-transformation with a bias-correction factor of 1·15 computed using the method of Duan (1983). The estimated fine-sediment yields were converted to loads by multiplying by drainage area. The fine-sediment loads

estimated with Equation 1 were then substracted from the measured annual fine-sediment loads at station 2262 to obtain estimates of fine-sediment loads resulting from highway construction activities.

Measurements of sediment mobilization and storage changes

Estimates of sediment mobilization and changes in sediment storage were based on field measurements of volumetric changes in landforms. Volume changes were converted to mass units of total sediment by measuring bulk densities of sediment sources using the method of Blake (1965). Proportions of fine sediment in sediment sources were determined with pebble counts (Wolman, 1954) and sieve analyses (Day, 1965).

Debris flows. Debris-flow scars were inventoried in 1990, 1991 and 1992, and locations were recorded. The number of debris flows each year was determined by subtracting the scars identified in previous years from the total number of scars. Length and width of debris-flow scars were measured remotely using an optical device employing the principle of similar triangles (S. D. Ellen, USGS, Menlo Park, CA, written communication, 1992). Average depth of debris-flow scars was estimated from tape measurements at four accessible scars. Annual debris-flow volumes were estimated by multiplying the lengths and widths of individual scars by the average scar depth and summing for all scars attributed to each year of the study. Samples of debris-flow deposits used for sieve analyses were wet-sieved through a 63 μm sieve after treatment with hydrogen peroxide to remove organic material.

Although field observations indicated that delivery of debris flows to channels was frequently incomplete, we assumed a delivery ratio of 100 per cent for sediment-budget calculations. Consequences of this assumption are discussed below.

Soil creep. Soil movement resulting from soil creep was monitored at eight hillslope sites (Figure 1) with modified Young pits (e.g. Lewis, 1976). These pits consisted of holes augured to bedrock or saprolite in which numbered sections of 2·5 cm PVC pipe were placed. Monuments consisting of steel rods were driven at least 0·5 m into the hillside on both sides of the pits along the contour. Downslope displacement of the pipe sections was measured with a ruler from a cloth tape stretched between the monuments.

Samples of hillslope soils were collected for bulk density and sieve analyses. Hydrogen peroxide was not used to remove organic material because the samples were also used for ^{137}Cs analyses. Samples were mechanically disaggregated instead.

Of the original eight hillslope sites, three were destroyed by construction before any rates could be measured (sites 1, 2 and 3). The remaining sites were considered inadequate to quantify spatial variations in soil creep rates, so a representative rate of 0·004 m a^{-1} over a depth of 0·50 m, based on previous studies in tropical climates (Lewis, 1976; Saunders and Young, 1983), was used in place of field measurements. The volume of soil mobilized by soil creep was estimated by multiplying the representative rate by the representative depth and the total length of channel affected by soil creep. This channel length was determined as the sum of the lengths of all channels, as determined from contour crenulations on the USGS Kaneohe and Pearl Harbour quadrangle maps (1:24 000, 1983), in an area extending from station 2262 upstream to a point halfway between hillslope sites 8 and 7. Hillslope site 8 is the farthest upstream site where soil creep was detected, and hillslope site 7 is the farthest downstream site where no soil creep was detected. Channel lengths were doubled to account for soil creep along both banks.

A delivery ratio of 100 per cent was assumed for soil creep. This assumption seems reasonable because soil transported by the creep process has little opportunity for deposition en route to a channel.

Channel sediment storage Erosion and deposition along the main stream channels in the study area were monitored with 25 monumented cross-sections. These cross-sections were located at miscellaneous measuring sites along the channel, in groups of two to four (Figure 1). Cross-sections were surveyed in 1990, 1991 and 1992 using level and rod. Annual cross-sectional areas were computed separately for each bank and the streambed by numerical integration of trapezoidal subareas above an arbitrary datum. Annual area changes for 1991–92 were calculated by subtracting the 1991 area from 1990 areas and 1992 areas from 1991 areas. Area changes are therefore positive for erosion and negative for deposition. Area changes for left and right banks were summed, and average annual changes in bank and bed areas were computed for each group of cross-sections.

Samples of bed and bank materials finer than 2 mm were collected for bulk-density and sieve analyses. Bulk-density analyses may underestimate the actual bulk densities of coarse channel-bank and streambed materials

because samples were not representative of the larger particles. Pebble counts (Wolman, 1954) were used to estimate the percentage of bank and bed material finer than 2 mm at each cross-section group. The percentages of fine sediment in bed and bank materials at each cross-section site were computed as the percentage finer than 2 mm, as determined from the pebble counts, multiplied by the proportion of the <2 mm fraction that was finer than 63 µm, as determined by sieve analyses.

To compute volume changes in channel storage of sediment, annual changes in bank and bed areas at cross-section groups were multiplied by the length of channel extending halfway to the adjacent cross-section groups both upstream and downstream. For the cross-section group at station 2262, the downstream end of the study area, area changes were multiplied by the distance halfway to station 2260. Area changes for sites 2255, 2252 and 2251 were applied to the lengths of channel marked as blue lines upstream of these sites on the USGS Kaneohe quadrangle map. Area changes for site 2251 were also applied to a major tributary that enters the main channel downstream of site 2252.

Volumes of channel erosion and deposition were therefore computed only for major perennial and intermittent channels, and not for the more numerous ephemeral tributaries. Soil creep was assumed to supply the sediment eroded from ephemeral tributary streambanks, hence a separate estimate of erosion along ephemeral tributaries was deemed unnecessary for the sediment budget. Although this assumption is reasonable for long-term sediment budgets, annual variations in bank erosion rates may have resulted in over- or underestimation of sediment delivery from ephemeral tributaries for our annual sediment budgets. Field observations indicate that little sediment was stored along the steep, narrow tributary channels.

All sediment eroded from the channel bed and banks was considered to be available for fluvial transport. This assumption is reasonable, because we did not observe mass failure of large intact blocks of bank material that remained in the channel following peak flows.

Miscellaneous sites 2252, 2255 and 2256 were destroyed during construction of the highway in 1992, and about 1·5 km of channel were lined with metal culverts and buried. The right bank and stream bed at site 2251 were buried by a debris flow in 1992. Computations of channel erosion for 1992 are therefore based only on measurements at stations 2262 and 2260 and at sites 2258.5, 2257 and 2251 (left bank only). Channel reaches lined with culverts were marked on topographic maps, and the lengths of these reaches were not included in the computations. Changes in streambed sediment storage during 1992 were assumed to be negligible in those reaches computed using data from site 2251.

Attrition experiments

Because this study concerned the transport of fine-grained rather than total sediment, attrition of coarse particles must be considered as a fine-sediment source. Coarse-particle attrition as a source of suspended sediment has been investigated previously by Dietrich and Dunne (1978) and Madej (1992). Both of these studies found attrition to be a major source of suspended sediment. Numerous other studies have documented substantial losses of coarse sediments as a result of abrasion during fluvial transport (Table I).

In the North Halawa Valley, the combination of basalt bedrock, warm climate and high rainfall has resulted in extensive chemical weathering of bedrock (e.g. Stearns and Vaksvik, 1935). Chemical alteration of bedrock to secondary minerals extends to tens of metres below land surface (e.g. Izuka, 1992). Coarse particles in near-surface sediment sources, therefore, are likely to be composed entirely of secondary minerals and so are likely to be much less resistant to mechanical abrasion than unweathered bedrock.

We used simple abrasion-mill experiments to estimate the amount of fine sediment resulting from attrition of coarse particles mobilized by natural erosional processes. The coarse (>63 µm) fractions of samples of debris-flow deposits, channel banks, and streambed material were individually tested in a rock-polishing tumbler made of soft rubber. The tumbler drum had a diameter of 11 cm and a length of 10 cm. Samples ranged from about 8 to 50 g dry mass and consisted mostly of sand and fine gravel, although a few samples contained coarse gravel. The samples were completely covered with deionized water and subjected to 8 km of simulated fluvial transport. This distance was selected to represent an average travel distance from mid-basin to station 2262. The drum rotated at a velocity of 0·4 m s^{-1}. After tumbling, samples were wet-sieved, oven-dried for 1–2 h at 80°C, and weighed. Attrition was calculated as the loss of mass of the coarse-material sample, expressed as a percentage of the original mass.

Table I. Results of previous studies of particle attrition

Reference	Lithology	Size range used	Transport distance (km)	Mass lost (%)	Experimental apparatus
Thiel (1940)	quartz, garnet, hornblende, apatite	0·5–2·0 mm	8000	22–84	tumbler
Morris and Fan (1962)	feldspar	1·2–1·4 mm	192	10	oscillating tubes
Moberly (1968)	unweathered basalt	sand	(50 h)	7–0	jarmill
Bradley (1970)	unweathered granite	gravel	256	8–30	flume
Bradley (1970)	weathered granite	gravel	256	27–99	flume
Dietrich and Dunne (1978)	basalt	sand	100	10	tumbler
Madej (1992)	schist, sandstone	2–90 mm	13	64–69	dry tumbler

On the basis of our field observations and calculations of bankful velocities and Reynold's numbers, forces exerted on coarse particles during peak flows in the stream are greater than those exerted during simulated transport in the tumbler. Our attrition results probably underestimate the rates of coarse-particle abrasion in the stream.

Two samples collected from channel banks at site 2256 were subjected to increasing cumulative lengths of simulated transport to assess effects of transport distance on attrition rates. Samples were removed from the tumber after each increment of transport, and wet-sieved with a 63 µm sieve. The coarse fraction was then oven-dried, weighed, and replaced in the tumbler for the next transport increment.

Two pairs of samples were analysed for ^{137}Cs activity to determine whether ^{137}Cs activity of fine sediment eroded from hillslopes differed from that of fine sediment resulting from attrition of coarse hillslope particles. Each pair consisted of the fine-sediment fraction sieved from a sample of a debris-flow deposit, and the fine sediment resulting from 8 km of simulated transport of the coarse particles from the same sample.

Sediment-budget calculations

Sediment-budget estimates for natural erosional processes were based on estimates of fine- and coarse-sediment mobilization and experimentally determined attrition rates. Fine-sediment loads resulting from attrition of coarse particles were determined by multiplying the mass of coarse sediment mobilized by each erosional process by the corresponding average attrition rate. The attrition rate for debris-flow samples was used for soil creep because both processes involve similar hillslope soils. Average attrition rates were applied to all coarse sediment mobilized by erosion of channel banks and bed for each channel reach where cross-section data indicated net erosion. All coarse sediment mobilized from channel margins was therefore assumed to undergo equal rates of attrition regardless of each location. Attrition was assumed to supply no fine sediment from channel banks or the streambed in reaches where cross-section data indicated net deposition. The total amount of fine sediment produced by each natural source was computed as the sum of the fine sediment resulting from *in situ* bedrock weathering and subsequent erosion and fine sediment resulting from erosion and subsequent attrition of coarse sediment. Estimates of sediment loads resulting from highway construction include both weathering-produced and attrition-produced fine sediment. Annual sediment-budget totals were computed as the sums of the estimated sediment production from all sources.

The error for each average value used in sediment-budget computations was computed as the standard error of the mean (e.g. Helsel and Hirsch, 1992). Total error for each term in the sediment budget was computed as a percentage using the method of Benjamin and Cornell (1970, p. 186). Net sediment-budget errors, or imbalances, were computed as percentages of the fluvial fine-sediment loads at station 2262 (henceforth 'fluvial loads') by subtracting sediment-budget totals from the fluvial loads, dividing by the fluvial loads, and multiplying by 100. Positive net errors indicate that the sediment budget fails to account for the entire fluvial load. Negative errors indicate that the sediment budget accounts for more sediment than was measured leaving the basin.

Aerosol analyses and budget computations

Sediment-source samples collected for quartz ^{137}Cs analyses were classified into five groups corresponding to the five sediment-budget sources: debris flows, soil creep (hillslope soils), channel banks, channel bed, and

construction (tunnel tailing, saprolite, and fill). Suspended-sediment samples from station 2262 were also analysed for quartz and ^{137}Cs contents. Because of the small mass of individual suspended-sediment samples, these samples were composited for ^{137}Cs analyses. All samples were wet-sieved, and only the fine (<63 μm) fractions were analysed.

The quartz contents of the fine fractions of suspended sediments and sediment source materials were determined by X-ray diffractometry (XRD). The methodology is described in Hill *et al*. (1997). Briefly, the method involves the development of calibration curves using standard mixtures of pure quartz obtained commercially and sediment-source materials collected in North Halawa Valley. Peak heights of sample diffractograms were compared to calibration curves to determine quartz content in percentage by mass. The lower detection limit was determined to 0·1 per cent quartz.

^{137}Cs activities were measured with a high-resolution, intrinsic germanium-detector gamma spectrometer. The methodology is described in Hill *et al*. (1997). Samples were typically counted for two-day periods. Uncertainties in the measured activities were calculated from the random counting error of each peak and background region for the sample and blank at the one standard deviation level, as described by Friedlander *et al*. (1981). The relative uncertainty in sample activities ranged from ±3 to ±58 per cent, and averaged ±15 per cent. Replicate counts of samples agreed, on average, to ±15 per cent. Detection limits for ^{137}Cs are dependent on sample mass and geometry (Keith *et al*., 1983), and ranged from 0·33 pCi g^{-1} for the smallest samples (suspended sediments) to 0·02 pCi g^{-1} for soil samples of sufficient mass to fill the largest counting jar.

The Kruskall–Wallis test (Iman and Conover, 1983) was used to test differences in the quartz contents and ^{137}Cs activities of the five sediment sources. This test is a non-parametric rank-based procedure that is insensitive to distribution of the data and can be used with data below detection limits. Average quartz contents and ^{137}Cs activities for sediment sources that include data below detection limits were computed using the method of Helsel and Cohn (1988).

Aerosol budgets are conceptually similar to sediment budgets in that they compare inputs, changes in storage, and outputs for drainage basins. Aerosol input results from atmospheric deposition, changes in storage result from erosion and deposition of aerosol-bearing sediment, and output is equal to fluvial transport in North Halawa Stream.

A crude estimate of atmospheric deposition for quartz was determined by multiplying the minimum annual quartz deposition rate estimated by Jackson *et al*. (1971) for ridges in the Koolau Mountains by the proportion of the basin area consisting of stream channels, highway construction sites and debris-flow scars. Quartz deposited on these areas was considered likely to be fluvially transported during a one-year period. Atmospheric deposition of ^{137}Cs was considered negligible on the basis of results of previous studies in the northern hemisphere (Ritchie and McHenry, 1990).

Changes in basin storage of quartz and ^{137}Cs were estimated by multiplying fine-sediment production from each source by the corresponding average sediment-source concentrations of quartz and ^{137}Cs. Attrition-generated fine sediment was included in the aerosol-budget calculations.

Concentrations of quartz and ^{137}Cs were not significantly correlated with streamflow or suspended-sediment concentration. Fluvial loads of quartz and ^{137}Cs were therefore determined by multiplying annual fine-sediment loads at station 2262 by the average quartz content and ^{137}Cs activity of suspended sediments collected at the station.

Aerosol-budget errors were computed in the same manner as sediment-budget errors. Because the error terms for the aerosol-budget estimates include errors associated with both sediment sources and aerosol concentrations, they are necessarily larger than corresponding sediment-budget errors.

RESULTS

Peak streamflows during the study period were moderate, with return periods of about two years in 1991 and one year in 1992. Our results are therefore representative of moderate streamflow conditions, and not high-magnitude events that might be more important for landform evolution and fluvial sediment transport.

Table II. Dimensions and volumes of debris-flow scars in the North Halawa Valley, water years 1991–92

Length (m)	Width (m)	Volume* (m^3)
Water year 1991		
37	5	37
15	7	21
7	7	10
33	7	46
7	1	1
15	14	42
11	4	9
3	3	2
35	9	63
9	7	13
15	4	12
40	3	24
37	4	30
14	4	11
15	11	33
	Total	354
Water year 1992		
48	6	58
78	4	62
10	3	6
32	2	13
4	3	2
15	3	9
7	4	6
5	5	5
5	5	5
41	6	49
7	3	4
3	2	1
12	3	7
	Total	227

* Volumes were computed using an average depth of 0·2 m, based on four field measurements of scar depths

Fluvial loads

The suspended-sediment load at station 2262 was 4730 Mg in 1991 (Matsuoka *et al*., 1992) and 3890 Mg in 1992 (Matsuoka *et al*., 1993). Fine (<63 μm) material constituted 40 to 100 per cent of suspended sediments in 1991 (Matsuoka *et al*., 1992) with an average of 85 ± 3 per cent, and from 47 to 100 per cent in 1992 (Matsuoka *et al*., 1993, and additional data in USGS Hawaii district files) with an average of 87 ± 6 per cent. The percentage of fine sediment was not strongly related to streamflow or sediment concentration in either year. The annual averages were therefore used to compute annual fine-sediment fluvial loads of 4020 Mg in 1991 and 3380 Mg in 1992.

Highway construction effects

Annual runoff at station 2262 during the study was within the range of the data used to compute Equation 1. Annual fine-sediment loads predicted with Equation 1 were 2710 ± 271 Mg for 1991 and 290 ± 46 Mg for 1992. Subtracting these estimates from the measured fluvial loads gives estimates of 1310 Mg in 1991 and 3090 Mg in 1992 that we attribute to highway construction.

Erosional processes

Debris flows Twenty-eight new debris-flow scars were observed throughout the study area during 1991–92. The average scar depth of 0·2 m, based on measurements at four scars, was used to compute debris-flow scar volumes of 354 m^3 in 1991 and 227 m^3 in 1992 (Table II). On the basis of the standard error of the scar depth

Table III. Bulk density and percentage fine sediment in samples of hillslope and debris-flow deposits, North Halawa Valley

Bulk density ($Mg\,m^{-3}$)	Mass % less than 63 μm
Hillslope soils	
0·39	–
0·43	–
0·49	–
0·31	–
0·57	–
0·12	57
0·34	55
0·87	50
1·40	51
0·86	46
1·37	48
Average=0·65	Average=51
Debris-flow deposits	
0·34	48
0·66	–
0·69	–
0·51	58
0·28	–
0·54	42
0·55	30
Average=0·51	Average=44·5

Table IV. Estimated changes in channel sediment storage, North Halawa Stream.

Station or site	Change in area (m^2)		Reach length (m)	Bulk density ($Mg\,m^{-3}$)		Fine sediment (%)		Total sediment contribution (Mg)		Fine sediment contribution (Mg)	
	bank	bed		banks	bed	banks	bed	banks	bed	banks	bed
Water year 1991											
2262	0·235	–0·223	998	0·92	0·80	20·6	2·4	216	–178	44	–4
2260	0·079	–0·068	1300	0·92	1·00	19·6	0·2	94	–88	19	0
2258·5	–0·045	–0·166	4150	1·03	0·72	19·0	1·0	–192	–496	–37	–5
2257	0·706	0·882	2170	0·74	1·00	12·8	0·1	1130	1910	145	2
2256	–0·086	–0·024	1220	0·76	1·04	5·0	1·2	–80	–30	–4	0
2255	0·016	–0·073	2860	0·80	0·80	2·5	11·4	37	–167	1	–19
2252	–0·048	–0·574	274	0·83	0·89	8·1	1·6	–11	–140	–1	–2
2251	0·056	–0·091	3270	0·62	0·89	10·9	0·7	113	–265	12	–2
							Total	1307	546	179	–30
Water year 1992											
2262	0·189	–0·190	998	0·92	0·80	20·6	2·4	174	–152	36	–4
2260	0·110	–0·194	1300	0·92	1·00	19·6	0·2	132	–252	26	–1
2258·5	–0·110	–0·090	4150	1·03	0·72	19·0	1·0	–470	–269	–89	–3
2257	0·098	0·037	4645	0·74	1·00	12·8	0·1	337	172	43	0
2251	–0·162	–0·517	3145	0·62	0·89	10·9	0·7	–316	–	–34	–
							Total	–143	–501	–18	–8

Positive numbers indicate erosion, negative numbers indicate deposition; –, missing data, assumed equal to 0 for computations

measurements, volume estimates are considered accurate within 22 per cent. The average bulk density of debris-flow deposit samples was 0·51±0·06 Mg m^{-3} and the average percentage of fine sediment in these samples was 44·5±6 per cent (Table III). Total-sediment mobilization by debris flows was estimated to be 180±44 Mg, including 80±22 Mg of fine sediment, in 1991, and 116±29 Mg, including 52±14 Mg of fine sediment, in 1992.

Soil creep The total length of channel bank subject to soil creep was estimated to be 52 400 m. Samples of hillslope soils had an average bulk density of 0·65±0·13 Mg m^{-3} and contained an average of 51±2 per cent of fine material (Table III). Using the representative rate and depth of soil creep based on published sources

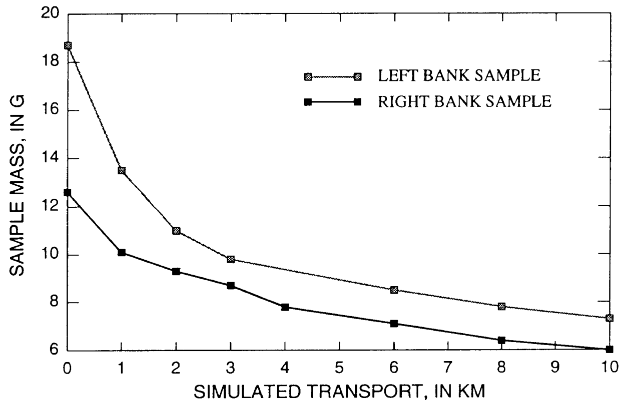

Figure 2. Mass loss of coarse particles in attrition experiments with variable lengths of simulated transport

(Saunders and Young, 1983), soil creep mobilized an estimated 68 Mg of total sediment, including 35 Mg of fine sediment, in both years of the study. A standard error of 50 per cent was assumed for volumes of sediment mobilized by soil creep.

Changes in channel sediment storage Sediment was deposited within most of the main channel during the study (Table IV). In 1991, banks eroded at stations 2262 and 2260 and at sites 2257, 2255 and 2251. At the other sites, banks aggraded. Streambed scour was observed only at station 2257. This spatial distribution of channel erosion was repeated in 1992 in the channel reaches not directly affected by highway construction, except that the left bank at site 2251 aggraded. Stream channels in 1991 were a net source of 1856±945 Mg of total sediment, including 149±91 Mg of fine sediment. Channels in 1992 were a net sink for 644±395 Mg of total sediment, including 26±16 Mg of fine sediment.

Attrition experiments

Five samples of debris-flow deposits, five samples of channel banks and three samples of streambed material were used in tumbler experiments with 8 km of simulated transport. Average attrition loss rates were 39±5 per cent for debris flows, 52±3 per cent for channel banks, and 36±4 per cent for bed material. These attrition rates are within the range of rates determined in previous studies (Table I) and do not seem unrealistically high in view of the extensive chemical weathering of bedrock and soils in North Halawa Valley.

Results of the two tumbler experiments using samples of debris-flow deposits with variable simulated transport distances indicate that attrition is most rapid in the first kilometre. The attrition rate declines more or less exponentially thereafter (Figure 2). Because abrasion is most effective in the first kilometre of transport, attrition may produce substantial amounts of fine sediment even for short transport distances.

The fine sediment produced by attrition of the two debris-flow samples used in the tumbler experiment had ^{137}Cs activities of 76 and 100 per cent of the activities of the original fine-sediment fractions. On the basis of these results, we concluded that fine sediment resulting from attrition is similar in terms of ^{137}Cs activity to fine sediment directly eroded from hillslopes. This result is not surprising given that most coarse-sediment particles are actually aggregates of clay minerals that readily adsorb cations.

We do not have similar direct evidence of quartz contributions from coarse-particle attrition. On the basis of the ^{137}Cs results discussed above and the highly weathered nature of coarse particles in the study area, we assume that quartz concentrations in fine sediment generated by attrition are equivalent to quartz concentrations in fine sediment in hillslope sediment sources.

Aerosol concentrations and fluvial loads

Average quartz contents for the five groups of sediment-source samples ranged from 0·1 to 1·2 per cent by mass (Table V). Quartz contents among groups differed significantly ($p = 0{\cdot}008$), although the averages for streambed and construction samples were equal.

Table V. Statistcal summary of quartz and ^{137}Cs concentrations in sediment source samples

Source	Statistic: *n*	NLT	Average	SD	SE
Quartz					
Debris flows	12	6	0·3	0·6	0·2
Soil creep	30	4	1·2	1·5	0·3
Banks	9	6	0·1	0·1	0·03
Streambed	8	4	0·4	0·4	0·1
Construction	10	2	0·4	0·6	0·2
^{137}Cs					
Debris flows	6	0	31·1	25·5	10·4
Soil creep	24	0	68·8	18·5	3·70
Banks	19	6	23·7	21·5	4·81
Streambed	5	1	10·4	8·14	3·70
Construction	12	9	2·59	1·85	0·37

n, Number of samples; NLT, number of samples below detection limits; SD, standard deviation; SE, standard error of the mean. Quartz statistics are reported in percentage by weight; ^{137}Cs statistics are reported in Bq kg^{-1}

Table VI. Statistical summary of quartz concentrations in suspended-sediment samples, water year 1991

Statistic	Streamflow ($m^3 s^{-1}$)	Suspended-sediment concentration (mg L^{-1})	Quartz* (%)
Average	4·89	1200	0·37
SD	3·54	1550	0·22
Median	4·16	573	0·34
Minimum	0·64	228	0·10
Maximum	25·5	8330	1·43

* A total of 109 samples was analysed, of which nine were below detection limits
SD, standard deviation

Table VII. ^{137}Cs activities of suspended sediments, station 2262, water year 1991

Sample	Date*	Average streamflow ($m^3 s^{-1}$)	Average suspended-sediment concentration (mg L^{-1})	^{137}Cs activity (Bq kg^{-1})	Detection limit (Bq kg^{-1})
C4	11-13-90	4·81	760	12·2	5·55
C5	01-27-91	4·11	3690	17·8	5·18
C6	03-11-91	4·47	1190	9·62†	9·99
C7	01-27-91	4·02	2090	12·2	7·77
C8	02-18-91 03-11-91	3·88	1890	15·2	11·5
C9	08-08-91 08-29-91 09-21-91	5·49	5360	5·55	4·81

* Month–day–year
† Below detection limit

Quartz contents of suspended sediments in 1991 ranged from values below detection to 1·43 per cent (Table VI). The average quartz content was 0·37±0·02 per cent. The 1991 fluvial quartz load at station 2262 was estimated at 14·9±0·89 Mg.

Average ^{137}Cs activities of sediment-source groups ranged from 2·59 to 68·8 Bq kg^{-1} (Table V). ^{137}Cs activities for the five groups were significantly different ($p<0.001$).

^{137}Cs activities of composite suspended-sediment samples in 1991 ranged from values below detection limits to 17·8 Bq kg^{-1} (Table VII). The average activity was 11·8±1·85 Bq kg^{-1}. Fluvial transport of ^{137}Cs at station 2262 in 1991 was estimated to be $47.4 \pm 5.14 \times 10^6$ Bq.

Table VIII. Estimated fine-grained sediment budget, North Halawa Valley

Source	Total sediment mobilized (fine + coarse) (Mg)	Fine sediment mobilized (Mg)	Coarse sediment attrition (%)	Fine sediment from attrition (Mg)	Fine sediment including attrition (Mg)	
					Est. load	Total error
Water year 1991						
Natural erosion						
Debris flows*	180	80	39	39	119	36
Soil creep	68	35	39	13	48	–
Banks	1310	179	52	712	891	330
Streambed	546	–30	36	687	657	553
Subtotal	2104	264	na	1451	1715	–
Construction†	–	–	–	–	1310	275
Total					3025	–
Water year 1992						
Natural erosion						
Debris flows*	116	52	39	25	77	23
Soil creep	68	35	39	13	48	–
Banks	–143	–18	52	280	262	155
Streambed	–501	–8	36	62	54	28
Subtotal	–460	61	na	380	441	–
Construction†	–	–	–	–	3090	186
Total					3531	–

* Computed using a delivery ratio of 100 per cent
† Computed as the difference between the measured fluvial fine-sediment load at station 2262 and the fine-sediment load estimated with the regional regression (Equation 1)
–, No data; na, not applicable

Table IX. Quartz and ^{137}Cs budgets for North Halawa Stream, water year 1991

Source	Quartz		^{137}Cs	
	Estimated load (Mg)	Error (Mg)	Estimated load (Bq$\times 10^6$)	Error (Bq$\times 10^6$)
Atmospheric	0·12	–	0·00	–
Debris flows	0·36	0·26	3·70	1·66
Soil creep	0·58	–	3·29	–
Channel banks	0·89	0·43	21·1	8·84
Streambed	2·63	2·31	6·81	6·18
Construction	5·24	3·04	3·40	1·11
Total	9·82	–	38·3	–
Fluvial load	14·9	0·89	47·4	5·14

Sediment and aerosol budgets

The sediment budgets (Table VIII) accounted for less fine sediment than was measured at station 2262 in 1991, and more fine sediment than was measured in 1992. Sediment-budget imbalances equaled 25 per cent of the fluvial load in 1991 and –4 per cent in 1992.

The quartz budget accounts for a total of 9·82 Mg of quartz in 1991, equivalent to 66 per cent of the fluvial quartz load (Table IX). Net error was therefore 34 per cent. The largest source of quartz was erosion related to construction (Table IX).

The ^{137}Cs budget accounts for a total of $38{\cdot}3\times10^6$ Bq of ^{137}Cs, equivalent to 81 per cent of the fluvial ^{137}Cs load (Table IX). Net error was therefore 19 per cent. The largest source of ^{137}Cs was bank erosion (Table IX).

DISCUSSION

Differences between sediment-budget and aerosol-budget imbalances in 1991 were relatively small, indicating that the sediment budget did not include large compensating errors. The sediment-budget imbalance of 25 per cent is therefore a reasonable measure of sediment-budget error. Knowing the magnitude of the sediment-

budget error, we can infer that erosion related to highway construction accounted for at least one-third (33 per cent, Table VIII) but no more than 58 per cent (33 per cent plus the 25 per cent error) of the fluvial load in 1991. By extension, we can use the 1992 sediment budget to conclude that highway construction accounted for roughly 90 per cent of the 1992 fluvial load, because the sediment-budget imbalance was only −4 per cent. The relative importance of construction as a sediment source was greater in 1992 than in 1991 because natural erosion produced less sediment and construction activities increased in 1992.

Attrition apparently plays a major role in generating fine-grained sediment. Attrition provided 85 per cent of all fine sediment produced by natural erosional processes in 1991 and 86 per cent in 1992 (Table VIII). The importance of attrition as a source of fine-grained sediment is probably the result of extensive chemical weathering that converts bedrock to aggregates of secondary minerals, as well as highly turbulent streamflow that provides energy for particle collisions.

Erosion of channel banks and streambeds was a major source of coarse sediment in 1991 (Table VIII). Attrition of this coarse sediment provided 82 per cent of the fine sediment attributable to natural processes (Table VIII). Bank erosion provided a smaller amount of weathering-produced fine sediment, whereas streambed storage was a net sink for fine sediment (Table VIII). Overall, channel erosion accounted for 39 per cent of the fluvial load at station 2262 in 1991.

Channel storage was a net sink for coarse and fine sediment in 1992 (Table VIII). Because channel margins eroded in some reaches (Table IV), however, some coarse sediment was mobilized, and attrition of these coarse particles produced 78 per cent of the fine sediment attributed to natural processes (Table VIII). Including effects of both channel storage and attrition, channels provided 9 per cent of the fluvial load in 1992.

We have considered changes in channel-sediment storage to be the result of natural sediment-transport processes. Highway construction may have affected these changes, however, by increasing runoff and hence channel erosion rates, or by adding to sediment deposited along channels. Increased runoff resulting from construction is unlikely in view of the small percentage of basin area affected by construction (e.g. Ziemer, 1981). However, construction activities probably added to sediment deposited along channels, especially in 1992, when estimates of channel deposition exceeded estimates of hillslope-sediment mobilization.

The hillslope processes of debris flow and soil creep contributed minor amounts of both coarse and fine sediment during both years of the study (Table VIII). The assumed delivery ratio of 100 per cent probably overestimates debris-flow sediment production. The average debris-flow scar depth of 0·2 m, however, was based on limited data and is only one-third to one-half the average scar depths reported in earlier studies in nearby basins (Wentworth, 1943; Scott and Street, 1976). Because our estimates of debris-flow sediment mobilization are only 2–4 per cent of annual totals listed in Table VIII, errors resulting from overestimating the debris-flow delivery ratio or underestimating debris-flow scar depth would not greatly alter our results.

CONCLUSIONS

Differences between sediment-budget and aerosol-budget imbalances in 1991 were relatively small, indicating that the sediment budget did not include large compensating errors. The sediment-budget imbalance of 25 per cent is therefore a reasonable measure of sediment-budget error. The sediment-budget imbalance cannot be attributed to a specific sediment source; however, because the magnitude of the sediment-budget error has been established, we can attribute at least one-third of the 1991 fluvial fine-sediment load to highway construction. Continued monitoring in 1992 indicated that highway construction produced 90 per cent of the fluvial fine-sediment load during that year. Erosion of channel margins and attrition of coarse particles provided most of the fine sediment produced by natural processes. Hillslope processes contributed relatively minor amounts of sediment.

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